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OBSERVATIONS ON THE EFFECT OF THE MONSOONS IN THE PRODUCTION OF PHYTOPLANKTON*

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INTRODUCTION

IT is well known that agricultural operations on land, food production especially in India, depend on the success or failure of the monsoons. Russel and Yonge (1947) while discussing seasonal cycle of plankton organisms in the tropical areas, state that "there are dry and rainy periods, the monsoons, and weather conditions that alternate with unfailing regularity during the year and it is more than probable that these secular changes may have their effect upon life in the sea". The effect of the monsoons has also been pointed out by Kow (1953) for the Malay region. In this brief account, it is proposed to show what are the effects of the monsoons on life in the sea and how they influence production therein.

BIOLOGICAL YEAR

The biological year for the Indian Peninsula may be said to commence in the middle of April or so. This is more or less the beginning of the spring in the temperate regions when life on land and water bursts into activity after the dark and dreary winter months. In India, this is about the time that the signs of the forthcoming south-west monsoon also become evident and whose outbreak and the thunder showers preceding same is eagerly awaited for the commencement of agricultural operations on land. The effect of the monsoon is felt all over the country though its intensity may vary at different places depending on the contour of the land. As applied to the sea, the biological year may be divided into (i) the south-west monsoon period from May to September and (ii) the north-east monsoon period from October to April following.

THE MONSOONS‡

The south-west monsoon sets in May or early in June at the southern end of the Peninsula and advances northwards striking the coast of Sind

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‡ Details regarding monsoons, currents, etc., have been drawn from Admiralty (1950) publication, and Sewell (1925, 1929).

in about 3 weeks. It is the beginning of the rainy season for most of the country. Its effect is felt more on the west coast of India and also North India, but not so much on the eastern half of South India owing to the presence of the Western Ghats. But this region also receives good amount of rainfall during the season and as most of the rivers of the country flow into the Bay of Bengal they carry lot of flood waters as there is heavy rainfall in the region of their sources also. By September, the south-west monsoon is spent but the rivers like the Ganges and Brahmaputra and the Irrawady still discharge flood waters into the Bay of Bengal.

The north-east monsoon normally begins early in the north. In the south, it becomes established only in December or so. It continues until about March. Its effect is not so much pronounced on the west coast of the Peninsula owing to the Ghats.

The west coast has a rainfall of over 100 inches; but at no locality on the east of the Ghats does the rainfall exceed 60 inches. Temperature conditions over most of the region is not very variable and there are no sharp fluctuations as far as the water is concerned.

OCEAN CURRENTS

West Coast

In the northern part of the Indian Ocean, the monsoons develop seasonal surface currents in opposite directions according to the time of the year. The east-going equatorial countercurrent, however, though lying mainly south of the Equator and extending a few degrees north of the Equator, is not reversed.

During the south-west monsoon, the coastal current in the Arabian Sea and the Bay of Bengal sets in a clockwise direction owing to the coastal conformation; and in a counterclockwise direction in November–January during the north-east monsoon. In the more open parts of the seas, the current takes the direction of a drift current due to the monsoon blowing at this time. This direction is easterly during the south-west monsoon and westerly during the north-east monsoon. The south-west monsoon circulation obtains from May–September; October is a transition month. From November onwards the current system in the Arabian Sea is as follows:—

November–January.—In the open waters the general set-up is westerly. Off the west coast of the Indian Peninsula, the predominant direction of the current to about 20° N. is north north-westerly; then, north-westerly becoming west north-westerly along the Makkram coast. Off the Arabian coast it is south-westerly.

February–April.—The predominant flow in the open waters is westerly or north-westerly. About the end of January, the counterclockwise circulation of November–January ceases, and a coastal current in the opposite direction (clockwise) is gradually established; thus, the coastal circulation is reversed while the north-east monsoon is still blowing. The monsoon begins to wane from the beginning of March.

The reversal of the coastal current is simultaneous along all parts of the sea. Off the Indus delta, the current is setting south. Further south, off the west coast of the Indian Peninsula, the reversal to south south-east occurs by the end of February. On the west coast the south-west monsoon is not established until June.

The reversal of the coastal current in the Arabian Sea during the latter part of the north-east monsoon is attributed to the formation of a gradient current caused by the cooling of the water at the head of the sea relatively to that farther southward. About this time (March), before the gradient current diminishes from diminishing temperature difference, the south-west monsoon begins and strengthens the clockwise coastal circulation as a normal current resulting from the wind.

May–September.—With the onset of the south-west monsoon or about its breaking, the East African Coastal Current already running in a northerly direction becomes increased in strength and constancy as also the clockwise coastal circulation in the Arabian Sea. The surface current in the open water flows in a general easterly direction everywhere northward of the west-going Equatorial Current. Often there are variations in the monsoonal drifts; however, the clockwise coastal circulation during the south-west monsoon is the most constant.

East Coast

The current circulation in the Bay of Bengal may now be considered. The year here also may be divided into periods.

June–August.—During this period, covering the commencement and a great part of the duration of the south-west monsoon, a strong surface drift flows eastward across the southern end of Ceylon between 0° and 10° S. latitude; this bends round to join the westerly flowing drift of the South Equatorial Current. The easterly drift on the north passes across the Bay of Bengal in a north-easterly direction and then east and south-east across the Andaman Sea and then through the Straits of Malacca. A smaller drift, coming from this latter channel, curves around north of Sumatra, passes for some distance south and possibly south-west along the Sumatran coast. There is a rotational movement in two of the areas; one lies close to the east coast of the Indian Peninsula extending north along the Orissa coast; the second is situated east of Ceylon. The isohaline contours suggest that there is a third movement of this nature lying off the centre of the mouth of the Bay at 4° N. and 88° E.; this is to be attributed to the current that sweeps in a north-westerly direction through the Straits of Malacca and along the north-east coast of Sumatra finally bending to the west and meeting the easterly flowing drift outside the Andaman Sea. In this, more or less, clockwise circulation in the Bay of Bengal, it is evident that the south-west monsoon coastal drift is also concerned as this carries the water around the tip of Peninsular India into the Bay of Bengal.

September–November.—This period covers the last stage of the south-west monsoon and beginning of the north-east monsoon. There are three sets of currents during this period in the Bay of Bengal: (i) Between south of Ceylon and the Equator, a strong easterly current passes which spreads fan wise at the south-east corner of the Island; part continues across the Bay of Bengal till near the Sumatran coast it becomes deflected either to the north or south; a second part bends northwards and enters the Bay of Bengal. (ii) Commencing at the head of the Bay of Bengal, a current flows towards the south-west, clearly the result of the north-east monsoon winds; it sweeps along the coast of India, reaches east coast of Ceylon and bends westwards, keeps close to the coast and reaches the Gulf of Mannar. (iii) Another current, the third, arises at the north end of the Andaman Sea and also passes towards the west and south-west; this soon after leaving the Andaman Sea is altered and by its impact with the first current, the easterly drift, a number of rotatory currents are set up in the centre and north-western parts of the Bay, in which the general trend of movement of surface mass is counterclockwise.

December–February.—The establishment of the north-east monsoon brings about great changes in the current system of the Bay. The currents show a cyclonic whirl. This is easy to recognize as it comes about owing to the influence of the north-east monsoon, the rotation of the earth and the coastal conformation. The water is driven from the Burmese coast across the Bay westwards against the Coramandal coast, becomes deflected by the coastal contour and preponderately flows north. Thus the whirl is caused. The centre of this lies 88° E. and 18° N. Constancy and current strength are now higher on the western side where the moving water mass is pressed against the coast. Between Ceylon and the mouth of the Godavari river, at approximately 17° N., the current develops and the water flows around the east coast of Ceylon into the open ocean, and some enter the Arabian Sea also.

March–May.—During this period very great changes take place in the direction of flow of the currents. During the early part of the period, a distinct double cyclonal circulation obtains at the head of the Bay, the currents moving round clockwise at two centres, 16° N. and 88° E., and 15° N. and 91° E., almost the same position as seen in December–January; at the mouth of the Bay, the currents are from east to west. With the commencement of the south-west monsoon winds in May, the cyclonal circulation disappears and the currents at the mouth of the Bay get reversed, and a well-marked surface drift from east to west is developed which bends at about the centre of the Bay and runs northwards into it. Near the Andamans the drift is in a south-west direction, a continuation of the currents produced by the north-east monsoon, while near the Nicobars, an easterly to north-easterly drift is developed.

The isohalines follow (*see* Sewell, 1928, 1929) the trend of movement of the water masses and show clearly the influence of the two monsoons on the sea-water.

Further, it may be mentioned here, that the Cold Antarctic flow, according to Carpenter (1887; *vide* Sewell, 1925, pp. 47–48) extends up to 10° N. and gradually surfaces. One arm of his flow extends to the Bay of Bengal, a second towards the Malay Archipelago and a third into the Arabian Sea. Upwelling of the waters of this current is very much augmented by the south-west monsoon winds. The influence of this bottom drift on the temperature and nutrient salt content of the Arabian Sea and other waters must be considerable. It is also known that there is an exchange of water between the Arabian Sea and Red Sea (Thompson, 1939). The foregoing review also shows that there is an exchange of water between the Bay of Bengal and Arabian Sea.

Influence of Monsoons on Phytoplankton Production

The data for nutrient salts for stations on the west coast: Bombay (Bal *et al.*, 1946), Calicut (Subrahmanyan, 1959 *b*), and east coast: Madras (Jayaraman, 1951; Ramamurthy, 1953), Gulf of Mannar and Palk Bay (Jayaraman, 1954), show that fairly high concentrations of phosphates, nitrates and silicates are present when compared with those for areas of rich production of phytoplankton elsewhere in the temperate or polar waters, particularly the values for Calicut. It is not likely that any of these nutrients acts as a limiting factor in these waters. There is no sharp seasonal fluctuation in the concentration of the nutrients on the east coast stations except silicates which register an increase during the rainy season, presumably owing to influx of freshwater. The values for all, however, keep oscillating. On the west-coast, a seasonal fluctuation is present (Subrahmanyan, 1959 *b*); but at no time, even during minima period, does the concentration go so low as to limit production.

Investigations for over 6 years on the west coast of India, at Calicut, has brought out some interesting facts (Subrahmanyan, 1959 *b*). The wind force during the months immediately preceding the south-west monsoon season, April in particular, is very high. This and the stormy conditions preceding the rainfall churn up the sea very much. The nutrient salts locked up in the mud are released in abundance into the water and these, phosphate, nitrate and silicate, and undetermined substances of organic nature, show an increase over the previous months. The organic substances are suspected to be of similar nature to those in soil decoctions and seaweed extracts which are used for promoting growth in cultures. Further, there is also an upwelling of the waters in the Arabian Sea under the influence of the south-west monsoon winds, and nutrient-laden waters are brought up and flow in the clockwise coastal circulation. The heavy rainfall helps bring down the salinity of the waters to favourable levels which together with the fall in the temperature to optimum ranges induces sexual reproduction and rapid multiplication in several Diatom species leading to the principal bloom of the year (Subrahmanyan, 1958 *a*, 1959 *a*).

After some time, the quantity of phytoplankton registers a fall and the minimum is reached in November. By this time, the north-east monsoon sets in. During this season also, phytoplankton shows one or two pulses of development, which are of a lower order when compared with the south-west monsoon bloom. The general flowering of the floral elements at this period also is brought about by the two factors conducive to that, *viz.*, a fall in salinity and temperature, the former particularly; though there is not much precipitation to affect the salinity of the water on the west coast, the lower salinity water from the Bay of Bengal entering the coastal circulation and the north-east monsoon winds bring about the favourable conditions. But the bloom is not a sustained one as salinity values go up owing to lack of freshwater influx from rivers (unlike the east coast) and reflux (*see* Huntsman, 1955) of oceanic water as a result of wind action which tends to move the surface waters away from the coast.

It has also been found, during this period, that sometimes a flowering of phytoplankton elements takes place when salinity and temperature values are also apparently not favourable. This flowering, however, does not appear to be a result of sexual reproduction and subsequent multiplication as is generally the case during the south-west monsoon season, but a result of vegetative multiplication. Such blooms are of short duration and occur during or after a period of strong winds which appear to mix up the water layers and make available certain essential growth-promoting substances from the lower layers or the bottom itself, for, there is always a good quantity of the inorganic nutrients present in the water (Subrahmanyan, 1959 *b*).

It may be particularly emphasized here that the floral elements concerned in the blooms are different each time, depending on several factors. This aspect is discussed in another paper.

Thus, on the west coast, there is a peak bloom of phytoplankton during the south-west monsoon season, occurring in July, generally; then during the north-east monsoon season, lesser pulses of development in December or January and in some years a bloom in March or April (Subrahmanyan, 1959 *a*).

Correlation of the Phytoplankton Blooms to the Monsoons—A Discussion

On the west coast of India, at Calicut (Hornell and Nayudu, 1923; George, 1953; and Subrahmanyan, 1959 *a*), at Trivandrum (Menon, 1945) and at Bombay (Gonzalves, 1947), the main bloom of phytoplankton is during the south-west monsoon season though there a slight time lag between these places depending on the time of establishment of the monsoon. A second pulse of development is not well emphasized at places other than Calicut. (Elsewhere the observations are few in number, of short durations and discontinuous, hence this remains to be determined.)

No account of plankton of the east coast so far has been of sufficient duration to enable one to assess the cycle and the factors governing the same in a reliable manner. Nevertheless, here also, the bloom of phytoplankton may be correlated with the monsoons.

In the Gulf of Mannar, around Krusadi Island, Chacko (1950) found the period of the maximum of the Diatom population to be from June–November. In the same Gulf, near Mandapam, more detailed investigation (Prasad, 1954) showed peaks of development in March, May and October in 1950, and February, August and November in 1951. (Such small changes between the years relating to peaks of production are common on the west coast also.) Though the south-west monsoon does not bring any rain to this area, it brings about very turbulent conditions in the Gulf of Mannar (Prasad, *l.c.*) as a result of which, presumably, essential nutrients are liberated from the shallow bottom; and, though the salinity values are high due to influx of water from the Indian Ocean, a bloom of phytoplankton develops which is comparable to the bloom in March or April on the west coast, a result of vegetative multiplication of the cells. The bloom of May 1950 and August 1951 at Mandapam may have been caused in this manner. From October onwards rainfall begins in this region due to the north-east monsoon winds and salinity also records a fall. The bloom in March and October 1950, and February and November 1951 appears to be related to the effect of this monsoon of the 1949–50, 1950–51 and 1951–52 respectively. The effect of the north-east monsoon in this region is similar to that of the south-west monsoon on the west coast of India, production of phytoplankton being related to fall in salinity, temperature and increase of nutrients. Further, as seen on the west coast during the south-west monsoon in some years, on the south-east coast also, the bloom, sometimes, occurs in two pulses. The same author, during a study of the plankton in the following years, July 1951 to June 1953, found at a station in the Gulf of Mannar (G) three distinct blooms, in January, April–May and October or November; and, at a station (P) in the Palk Bay, one single prominent peak during the summer months, May–June, and another in October–November (Prasad, 1956). In these instances also, the blooms in April–May at Station G and May–June at Station P appear to be due to the south-west monsoon influence; and the peaks in January and October–November at G and October–November at P due to the north-east monsoon. The change in the timings of the blooms depend on the onset of the monsoon and also on the fall in the salinity due to precipitation and water of low salinity entering the area in the coastal circulation. It may be mentioned here that the south-west monsoon first strikes the tip of the Peninsula and advances northward, and the stations in the Gulf of Mannar and Palk Bay are farther south of Calicut (between 9° 13′–9° 20′ N. and 79° 05′–79° 15′ E.) where, obviously, the effect of the monsoon will be felt much earlier. Further, it may be noted that the period of bloom of phytoplankton in this area is nearer to the transition months between the monsoons when there is a change in the direction of the winds and currents. The Gulf of Mannar and Palk Bay are shallow seas, the depth varying from 2½–6 fathoms only; naturally, therefore, wind may have a great role in influencing the production of phytoplankton as in the Great Barrier Reef region (Marshall 1933; *see* also Subrahmanyan, 1959 *b*).

Two sets of observations are available for the Bay of Bengal off Madras, one published in 1931 (Menon) and the other 22 years later in 1953 (Ramamurthy). According to Menon, the general maximum which occurs in April–May is a culmination of a regular and constant Diatom increase beginning in the September preceding, though there is a subsidiary peak in December. According to Ramamurthy, Diatom production is rich in February, April, May, August, September, November and December. The two accounts are comparable except that Ramamurthy records high production in August–September; in fact, in the first year of his observation, this peak is of a higher order than the April–May production. Unfortunately, neither of the accounts contain data even for two full years; how far the cycle would repeat itself cannot be judged. Nevertheless, it is seen that there are pulses of production during south-west and north-east monsoon seasons. The poorest month for plankton here appears to coincide with the period of the reversal of the coastal current, September–November (south to north flow in the earlier period becoming north to south, Sewell, 1929), resembling conditions in November on the west coast. Though the south-west monsoon does not bring any rainfall to this region, its effect is widespread throughout the rest of India so much so, owing to the heavy rainfall at the sources of the large river systems of India, an enormous quantity of water comes to be discharged into the Bay of Bengal and even after September this continues. From June–August this effect through river influx appears to be not felt at Madras since the coastal circulation at this time tends to move the water away from the region and in a northerly or north-easterly direction and brings in also water of a higher salinity from the Indian Ocean in the south. Only after September, with the reversal of the current bringing in water of a lower salinity also from the north and the setting in of the north-east monsoon, optimum salinity values appear to be reached leading to pulses of phytoplankton production. After recording a fall in the standing crop in January, the Diatom population increases again leading to another peak in April or May. It does not appear to be certain yet when the main production occurs at Madras; continuous work for several years appears to be needed here.

At Vizagapatnam, data are available only for about two years (Ganapati and Rao, 1953; Ganapati and Murthy, 1955). Here also, two pulses of production are reported, a "spring" maximum in February-April and an autumn one in October-December. The accompanying figure (Ganapati and Murthy, 1955, p. 92, Fig. 2) shows the Diatoms attaining a peak in April, the quantity falling till September to a low crop and two smaller peaks in November and February after the scarce period in September and October. The *standing crop*, as seen from the figure, is of a higher order from April–August, even after the fall from the maximum, than even the secondary peaks in November and February. While Madras and regions south of it do not have any appreciable rainfall* during the south-west monsoon, Vishakapatnam receives its major

* Data relating to Meteorological conditions, etc., were obtained by courtesy of the Director, Regional Meteorological Centre, Madras. Data not quoted here in order to save space.

portion of rainfall during this season and also some in October, November and December of the north-east monsoon period. The "spring" bloom at Vishakapatnam begins when the pre-monsoon showers occur there and a high standing crop is maintained from April–August; this would have been of a higher order and of prolonged duration if the salinity had not fallen to a very low level in the following month owing to the local precipitation as well as discharge of rivers in the environment and the change in the current circulation also bringing in water of low salinity. On this coast, as on the west coast, the standing crop is of a higher order from May–August with a number of pulses of development during the north-east monsoon period.

It is interesting to note that while there are several species of Diatoms and other phytoplankton elements common to both the Arabian Sea and Bay of Bengal, quite a good number are not so* (Subrahmanyan, 1946, 1958 *b*). This may be due to salinity conditions; salinity values, on the whole, are of a lower order in the Bay of Bengal and quite a good portion of the Bay may be considered estuarine. In the Arabian Sea, conditions are more oceanic and a higher salinity prevails, probably also due to the influx of Red Sea water into the Arabian Sea, besides the waters from the equatorial region.

It is not clear how far the discharge of the rivers into the sea around the Indian Peninsula contributes to its fertility. Differing views exist on this aspect and it would seem that no generalization is possible for all the nutrient salts; conditions may differ according to the area and nature of land over which the rivers flow and the effect of the effluents flowing into them before they reach the sea. For the west coast of India, there is some evidence for an enrichment of the sea by freshwater influx; it has also been found that the sea bottom mud definitely contributes to the enrichment of the water and concentration of some of the salts (Subrahmanyan, 1959 *b*). For instance, phosphate content of the water and the bottom mud have been shown to have an inverse ratio (Seshappa, 1953); this confirms an exchange of substances between the bottom mud and the water. The changes connected with mud-bank formation, caused perhaps by the south-west monsoon and currents, also appear to exercise considerable influence on the fertility of the waters (*see* also Panikkar, 1952, p. 756).

Sewell (1952) also refers to the high fertility of the waters of the Arabian Sea and after discussing the richness of the fauna (*l.c.*, pp. 714–15) and the high percentage of organic matter in the bottom deposits of that sea, he states (*l.c.*, p. 716): "The origin of this high percentage of organic matter in the bottom deposit is to be found in the amazingly rich zooplankton that is present, along the African and Arabian coasts and extending eastward towards India, during the months of the south-west monsoon and shortly after. The cause of this rich plankton is to be found in the upwelling of deep water all along the coasts of East Africa and

* An account on the qualitative and quantitative distribution of the various species of Diatoms and Dinophyceæ is under preparation.

Arabia under the influence of the south-west monsoon wind. The upwelling water is rich in nutrient salts, nitrates and phosphates, and thus provides the necessary conditions for a rich outburst of phytoplankton that is followed by an amazingly rich zooplankton; and as the dead bodies of these organisms sink to the bottom and accumulate in the mud, they provide nutriment for large numbers of other animals in the zones above and below the azoic region where there is sufficient oxygen to support life."

For the east coast of India, unfortunately, there have been no intense and continuous investigations of the sea-water and that of the large river systems. There is a probability that for this region, there may be a definite contribution by the rivers concerned, as they are large and flow through vast areas carrying an enormous quantity of silt and might contribute to the enrichment of the Bay of Bengal as does the river Mississippi of North America to the Gulf of Mexico (Riley, 1937–38). The blooms of phytoplankton may bear a closer relationship to this factor which in turn is linked with the monsoons. It may be mentioned here that upwelling of water has also been demonstrated off Vishakapatnam coast (La Fond, 1954).

From the above review, the correlation between the monsoons and production of phytoplankton in the Indian waters becomes evident. Obviously, the sequence is brought about by the effect of the monsoon winds mixing up the water layers and the sea bottom besides bringing about precipitation and also the movement of the water masses. It is clear from the data for current circulation in the Arabian Sea and Bay of Bengal that there is an exchange of water between them and also other regions such as the Indian Ocean, Red Sea and the Antarctic. The isohalines (Sewell, 1929) follow the trend of the movement of the water masses and show clearly the influence of the monsoon rainfall on the sea-water. These factors also bring about an increase in the nutrient salts and the cumulative effect is conducive to phytoplankton production. Thus, the fertility of the Indian coastal waters also, it would appear, is dependent on the monsoons as is agricultural production on land.

SUMMARY

An account setting out the influence of the south-west and north-east monsoons on the hydrological conditions and thereby on the production of phytoplankton is given with reference to the writer's work on the west coast of India and several other investigations on the west and east coasts of India. The correlations of the phytoplankton blooms at the different places to the monsoonal period are pointed out and discussed. The fertility of the Indian waters appears to be controlled by the monsoons.

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